International Conference on Case Histories in Geotechnical Engineering

(2013) - Seventh International Conference on Case Histories in Geotechnical Engineering

01 May 2013, 2:00 pm - 4:00 pm

A Comparison of Three and Two-Dimensional Analyses of Rockfill Dams in Narrow Valleys (A Case Study: The Vanyar Dam)

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A COMPARISON OF THREE AND TWO-DIMENSIONAL ANALYSES OF ROCKFILL DAMS IN NARROW VALLEYS (A CASE STUDY: THE VANYAR DAM)

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ABSTRACT

A two-dimensional analysis of the largest cross-section of earth dams may generate appropriate results provided that the dam is located in a U-shape valley. The Vanyar dam has been constructed in a narrow valley. With regard to the geometrical considerations of the valley, there is no plane strain condition throughout the long side of the dam. In this research, the results of three and two-dimensional numerical analyses of the Vanyar dam are compared in terms of settlement, pore water pressure, and total vertical stress. These analyses were carried out by a finite difference method through FLAC-3D and FLAC-2D softwares. In order to verify the results of the analyses, the settlement data recorded by the instruments in the body of the dam are compared to those provided through the numerical analyses. The results of the three and two dimensional analysis show that the settlements in the upper half of the height of the dam have a suitable adaptation. Moreover, the two- dimensional analysis shows the settlements in the lower half of the height of the dam more than those shown by the three-dimensional analysis. Furthermore, in terms of total vertical stress and pore water pressure, the two-dimensional analysis shows the values throughout the height of the dam more than those shown by the three-dimensional analysis.
Key words: Earth dams, three and two dimensional numerical analysis, instruments, settlement, total vertical stress, pore water pressure.

INTRODUCTION

Earth dams are important geotechnical structures that need to be designed and analyzed precisely for safety and proper performance. To ensure accuracy of this analysis, monitoring systems are installed in the body of the dam during construction and operation. The earth dams are generally constructed on a wide (U-shape) valley. Based on geometrical and topographical conditions of the valley and body of the dam, two-dimensional numerical analysis is performed on the largest cross-section of the earth dams. Due to some advantages of the earth dams, their construction on various geometries of valleys has been recently increased. The narrow valleys are natural obstacle for constructing this kind of geotechnical structure which needs to apply a three-dimensional analysis.

Heydari, 2003 showed that the two-dimensional analysis does not obtain precise results for those earth dams which are located on the valley with $\frac{L}{H}<4$) L and H are length and height of the valley, respectively) and it has to use a three-dimentional numerical modelling for the purpose of analysis design and. In addition, Lefebvre, 1973 has concluded that a two-dimensional analysis is not applicable for analyzing the earth dams constructed on steep valleys. Guangfeng et al., 2009 performed the research on three earth dams including Alban, Malaysia and Vernon. Their results demonstrated that settlements of the dams during construction have good agreement with settlements obtained from three-dimensional analysis, while two-dimensional numerical analysis provides inaccurate results. Einsenstein et al., 1972 found that the two-dimensional analysis on a homogeneous earth dam with body slope (1V:2H) predicts a greater settlement in comparison with three dimensional analysis. Tavallali, 1997 conducted three and two dimensional numerical analyses on La-Villita and Malpaso dams which have arc-shape crest. The results revealed that plane strain assumption is not able to predict precise results in comparison with the three-dimensional analysis.

Vanyar dam was constructed on a narrow valley with $\frac{L}{H}\approx 3$.

It is assumed that the two-dimensional analysis cannot provide the real behavior of the Vanyar dam since location of the site makes the dam unsuitable for plane strain modeling. The main objective of this research is evaluation of the effects of two and three dimensional numerical analyses on the behavior of Vanyar dam at the end of construction. The instrumentation data extracted from monitoring system have been used to verify the results of numerical analysis. To verify of the results of numerical analyses, the data recorded from instruments have been compared with those extracted from two and three dimensional numerical analyses at the large cross-section of this dam. Settlement, vertical stress and pore water pressure are the three selected parameters which have been considered for evaluation of the numerical analysis as well as the recorded data from the instruments.

VANYAR DAM

The Vanyar rock fill dam has been constructed in 5km north east of Tabriz city on the Ajichai River. The core of the dam is protected by two layers of filters in upstream and downstream with the shells being composed of two parts including transitional and rock fill layers. Table 1 lists technical characteristics of the Vanyar dam.

Table 1. Technical characteristics of Vanyar dam and its reservoir (Ghods-Niroo Co, 2010)

Dam detail	Value
Height of crest from bed rock	92m
Height of crest from river bed	45m
Dam crest elevation a.s.l	1504m
Normal water level a.s.l	1498m
Length of dam crest	278m
With of dam crest	10m
Total dam volume	$3.61\times10^{8}m^{3}$
Body dam materials volume	$1.7\times10^{6}\,m^{3}$
Dam slope up-stream	1:2.3
Dam slope Down-stream	1:2.1 + Berm
Total reservoir area	12.33 Km^{2}

The body of Vanyar dam is instrumented by a monitoring system in five cross-sections. Fig 1 depicts the location of instrumentation in the cross-sections of A, B, C, D, and E on a longitudinal section of the dam. Various instruments were devised in the body of this dam. The main instruments used in this research to verify the results of numerical analysis include Magnetic Settlement Detector (SD), Vibrating Pressure cells (PC), and Vibrating Wire Piezometers (VP). These instruments have been located in the core of the dam in three axes and at different levels of its height. The location of the instruments in cross-section "C" has been illustrated in Fig 2. "C" letter has been added to the beginning of the name of aforementioned instruments in the "C" cross-section.

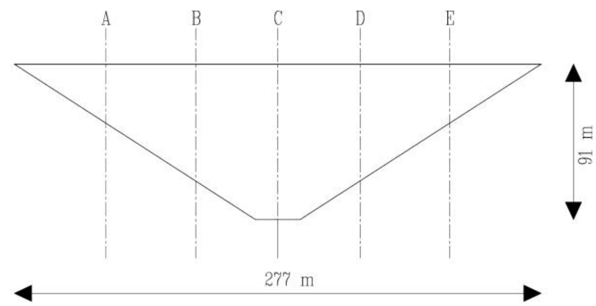


Fig.1. Cross-sections A, B, C, D, and E for installing instruments on a longitudinal section of Vanyar dam

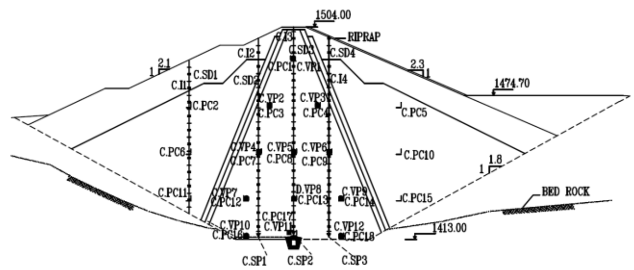


Fig. 2 Layout of the settlement tubes, the inclinometers, pressure cells, and piezometers in Section C (Ghods-Niroo Co, 2010)

NUMERICAL MODELLING

Three and two dimensional numerical models were used to evaluate mechanical behavior of Vaniyar dam at the end of construction. Two softwares of FLAC 3D (Itasca, 2005) and FLAC2D (Itasca, 2003) were utilized for numerical modeling of the dam, which worked based on finite difference method. Figs. 3-a and 3-b show the mesh generation for two and three dimensional models of the Vanyar dam. The horizontal boundaries of the models were extended for 110 m to upstream and downstream, which are more limited in comparison with seepage analysis. Then a three-dimensional model was extended about 50 m from the supports to both sides of the dam along crest of the dam.

Boundaries of both side of the dam are constrained against lateral movement while bottom boundary of the dam is also constrained against lateral and vertical movements. To generate initial stresses, all parts of the dam in the model were removed and foundation of the dam was simulated alone. Stage construction is used to model and analyze body of the dam. Above the foundation, the dam was simulated in 18 and 28 layers in three and two dimensional models respectively through stage construction method.

The same mechanical properties were considered for both three and two dimensional models which were obtained from the laboratory tests on the resource materials. In addition, Elastic-plastic model incorporating plastic Mohr-Coulomb failure criterion was applied to analyze the dam. Table 2 lists properties of the materials for various parts of the Vanyar dam.

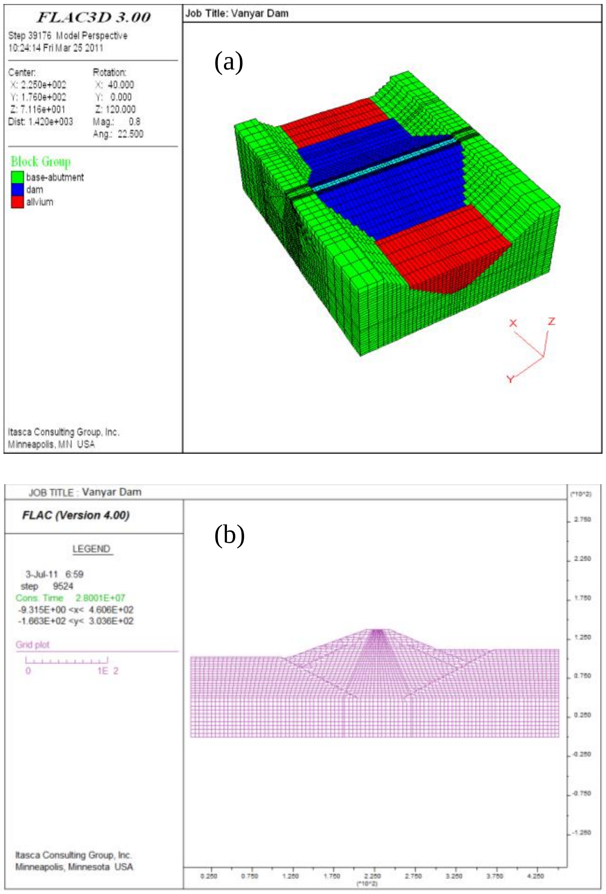


Fig.3 Mesh generation of three and two dimensional models of Vanyar dam by FLAC 3D&2D software

Table 2. Properties of materials using for three and two dimensional numerical analyses (Ghods-Niroo Co, 2007)

Material type	E(Kpa)	υ	C (kPa)	φ	$\gamma_d (kN/m^3)$	ψ	K (m/s)
Clay core (CU)	20000	0.35	15	30	20.04	1	5e-8
Disposal	30000	0.35	0	28	19.20	0	1e-5
Alluvial foundation	35000	0.3	20	30	19.23	2	1e-6
Bed rock	390000	0.37	60	50	20	8	1e-9
Rock fill shell	81600	0.3	0	48	19.25	8	1e-4
Transient shell	60000	0.34	0	38	20.27	7	5e-4
Filters	40000	0.39	0	33	18.5	5	1e-5

RESULTS AND DISCUSSION

In this section, the results of performed stress-strain analysis on three and two dimensional models are evaluated. The cross-section "C" has been selected as a critical cross-section to study various parameters extracted from numerical analyses and recorded data from the instruments. The following results are allocated to discuss settlements, total vertical stresses and pore water pressures which are obtained from the numerical analysis and the data recorded from instruments.

Settlements

The settlements which are extracted from three and two dimensional numerical analyses in the place of instruments are compared with those recorded by the instruments in this part. Fig 4-a and Fig4-b show the settlement results at the middle cross-section of the dam for three and two dimensional numerical models, respectively. It shows that the trend of settlements fairly agrees with three and two dimensional analyses. Regarding to Fig 4-a, the maximum settlement obtained from three-dimensional numerical analysis is about 88.14 cm. It occurs at 48 m above the bed rock and height ratio of $\frac{z}{h}=0.55$ in axes of the dam. This settlement is about one percent of dam height which is in agreement with the existing literature. On the other hand, the maximum settlement obtained from the two-dimensional numerical model was calculated about 94 cm which is located 37 m above the bed rock with the height ratio of $\frac{z}{h}=0.42\cdot$

Fig 5 provides the settlements obtained from three and two dimensional numerical analyses with those recorded from the instruments in "C" cross-section. In the location of the C.SD3, the results of settlements in two–dimensional model are about 20 cm (23%) more than those in three-dimensional model at the lower half of the dam. On the other hand, there is a good agreement between three and two dimensional analyses in the upper half of the dam (h/2 to h) as geometry and loading both satisfy the plane strain conditions along 200 m of longitudinal section of the dam.

The results of settlements, in the numerical analysis, at the bottom half of the dam (0 to h/2) are significant for three and two dimensional models, because the geometry of narrow valley does not satisfy the plane strain conditions in this area of the cross-section. In other words, the stiffness of supports of both sides and narrow valley have maximum effects on settlements of the dam. Consequently, the settlements obtained from the three-dimensional analysis are less than those obtained from the two-dimensional analysis. Therefore, the settlements recorded by the instruments approach to the results of three-dimensional analysis.

It can be stated that almost all of the settlements recorded by the instruments are less than those obtained from the three-dimensional analysis except CSD3. Nazari Afshar et al., 2011 found the similar results by performing a three-dimensional numerical analysis on Maroon dam.

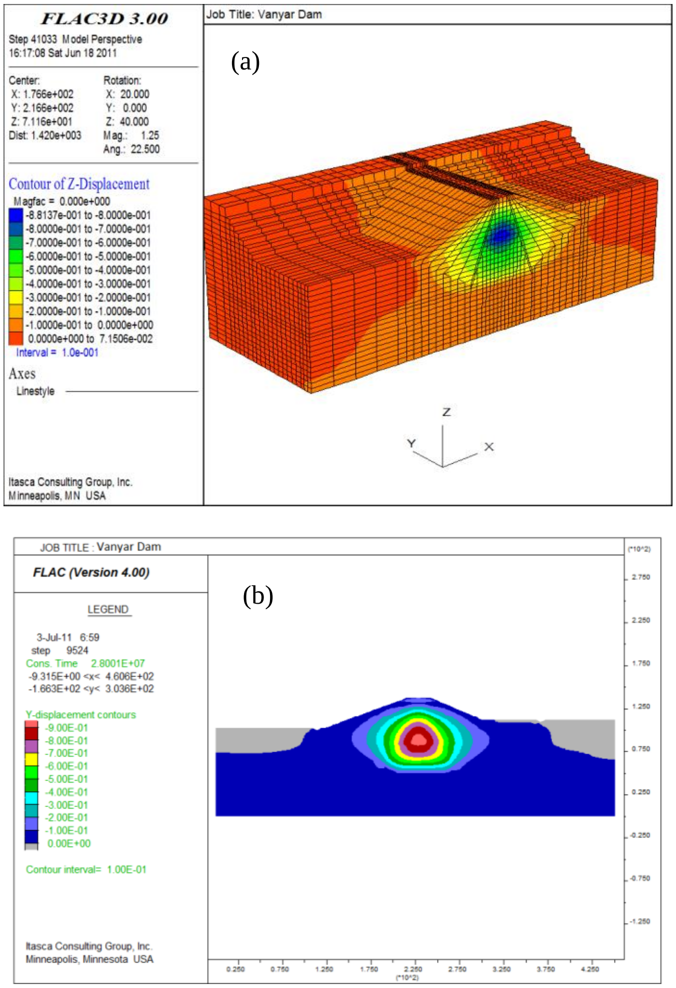
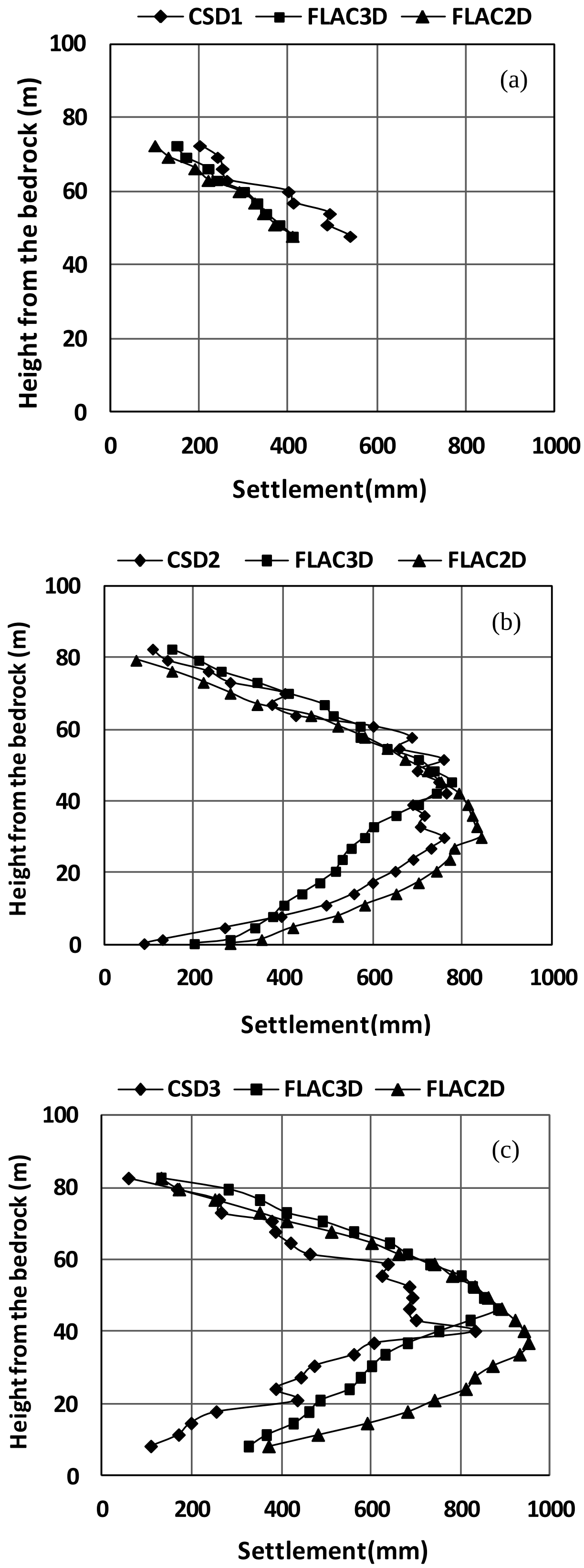


Fig.4 settlements contour for a. three-dimensional model b. two-dimensional model

During the compaction by heavy rollers and to prevent damage to the settlement detectors, the soil around the settlement detector is compacted by manual compaction. This can create a low stiffness area in the soil around the settlement detectors. Consequently, the settlement detectors recorded values more than those obtained by the three-dimensional analysis. On the other hand, a lower stiffness area shows a greater settlement in comparison with a high stiffness area when subjected to the same overburden pressure. This phenomenon is not usually assumed because non-homogeneity of the materials is not considered in the numerical simulation of the dam (Nazari Afshar et al., 2011; Palasi et al., 2003; Karimi, 2006).

Based on Fig 5, the recorded settlements by CSD3 are less than those obtained from numerical analysis. The consultant engineers of the Vanyar dam stated that the settlement detector CSD3 was installed with some time delays in comparison with other settlement detectors. This time delay can interpret the aforementioned differences. As a result, the settlements recorded from the instruments have more consistency with the three-dimensional numerical analysis.



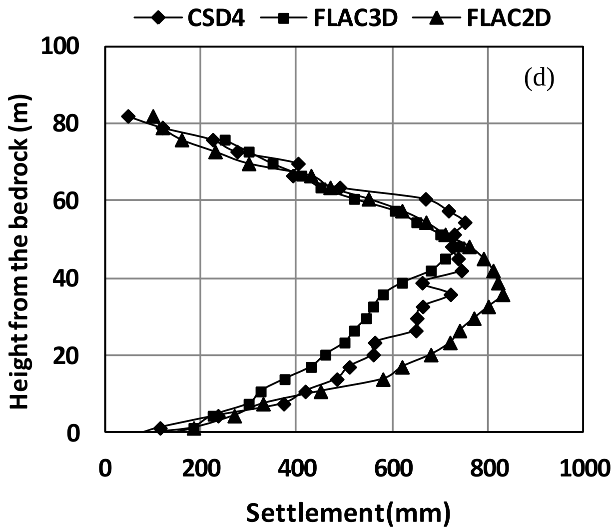


Fig. 5. Comparison between the settlements obtained from three and two dimensional numerical analyses and the data recorded from the instruments in "C" cross-section at the end of construction for a. CSD1, b. CSD2, c. CSD3, and d. CSD4

Total vertical stresses

The data recorded from the pressure cells may not have enough precision due to the lack of sufficient accuracy in the instruments utilized. It is a one of the reasons for performing numerical analysis of earth dam (Hunter, 2003). The difference in stiffness of the shell and core materials due to the difference of elasticity modulus of core and shell causes to create a non-uniform settlement tendency in the vicinity of core and shell. The friction between shell and core causes to transfer a portion of the core weight to the shell. This phenomenon is called Arching which creates a low stress area adjacent to core and shell as one main causes of Hydraulic Fracturing in the earth dams. Figs. 6-a and 6-b depict contour of the total vertical stresses in three and two dimensional numerical models. The Arching phenomenon is observed in the vicinity of core and shell. It has more clarity in the two-dimensional model. In addition, arching is observed adjacent to alluvial and shell because of the difference in stiffness of these two materials. Furthermore, Fig 6 demonstrates that the schematic shapes of contours obey from geometry of the dam. Experimental studies on Martin dam confirm the aforementioned results (Fell, 2005).

Fig 7 illustrates the variations of total vertical stresses on the core axis obtained from three and two dimensional analyses as well as the total vertical stresses recorded by the pressure cells in "C" cross-section. Regarding to Fig 7, total vertical stresses obtained from three and two dimensional analyses are more than those recorded by pressure cells in all of the points in the core axis. It can be interpreted that the soil around the pressure cells was compacted by light rollers manually to prevent damages to the pressure cells. Therefore, the local Arching is created in the place of the pressure cells. Consequently, the instruments show the stresses less than those obtained by numerical analyses.

In addition, the total vertical stresses obtained from two-dimensional analysis are about 15% higher than those calculated by three-dimensional analysis. This difference becomes more significant by increasing overburden pressures. Lefebvre, 1999 reported that the difference is 23% in average for the earth dam constructed on narrow valleys. Fig 8 depicts variation of the vertical stresses obtained from three and two dimensional analyses at levels of h/2 and 2h/3 of core width in the "C" cross-section. Based on Fig 8, there is a low stress area in the vicinity of both core and filter. In addition, the total vertical stresses obtained from two-dimensional numerical analysis are more than those calculated from three-dimensional analysis especially in the vicinity of core and filter.

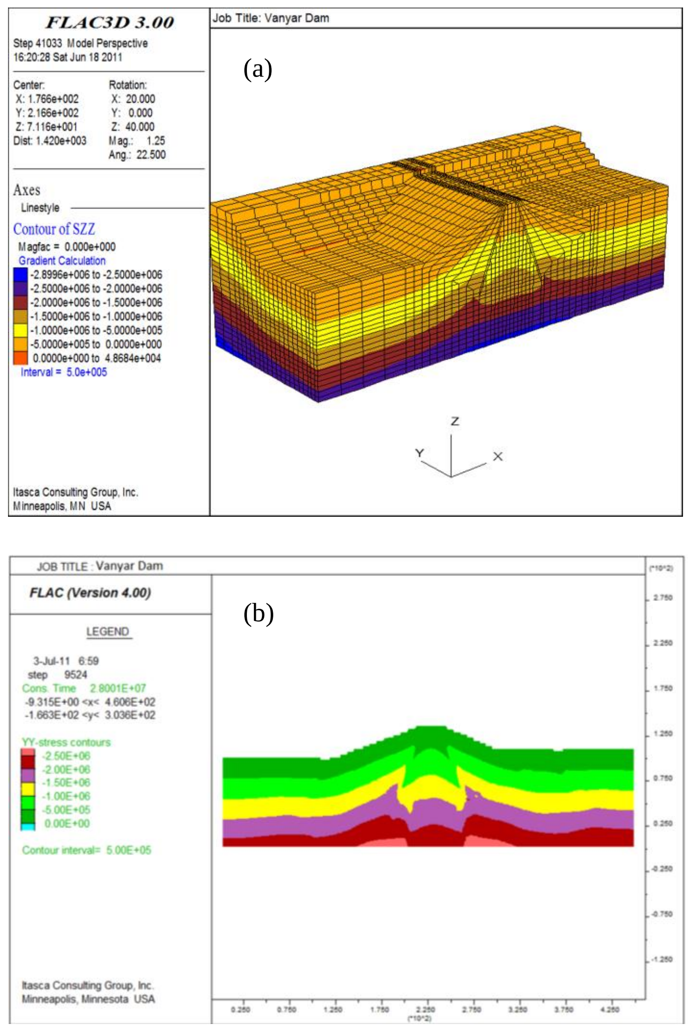


Fig. 6 total vertical stresses contours at the middle cross-ection of vanyar dam in the a. Three –dimensional numerical model b. two-dimensional numerical model

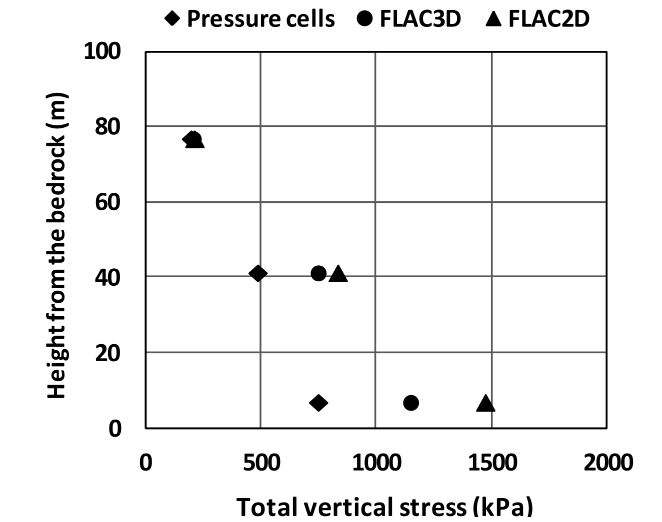


Fig. 7 variation of total vertical stresses on the core axis in "C" cross-section obtained from three and two dimensional analyses, and the recorded data by pressure cells

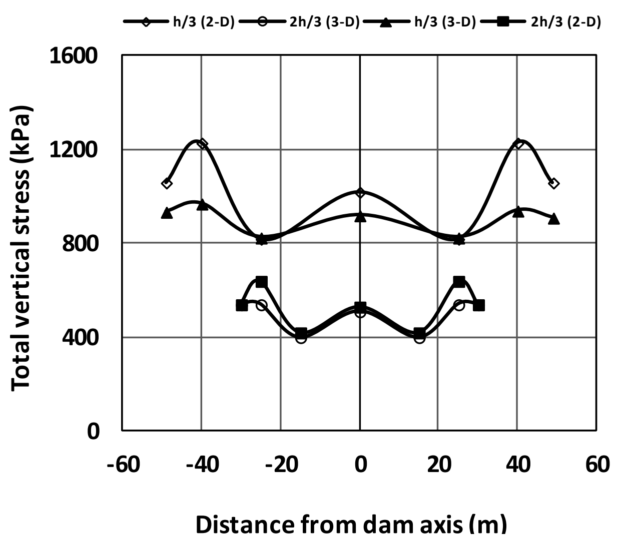


Fig.8. Variation of total vertical stresses obtained from three and two dimensional numerical analyses at h/2 and 2h/3 levels of core width in "C" cross-section

<u>Pore water pressure</u>

Pore water pressure is an important parameter that can evaluate hydraulic fracturing in the core of the dam when compared with total vertical stress. In this section, the pore water pressures are compared in three and two dimensional numerical analyses with those recorded by the instruments. Figs. 9-a and 9-b show contours of the pore water pressures for three and two dimensional numerical models respectively in the "C" cross-section.

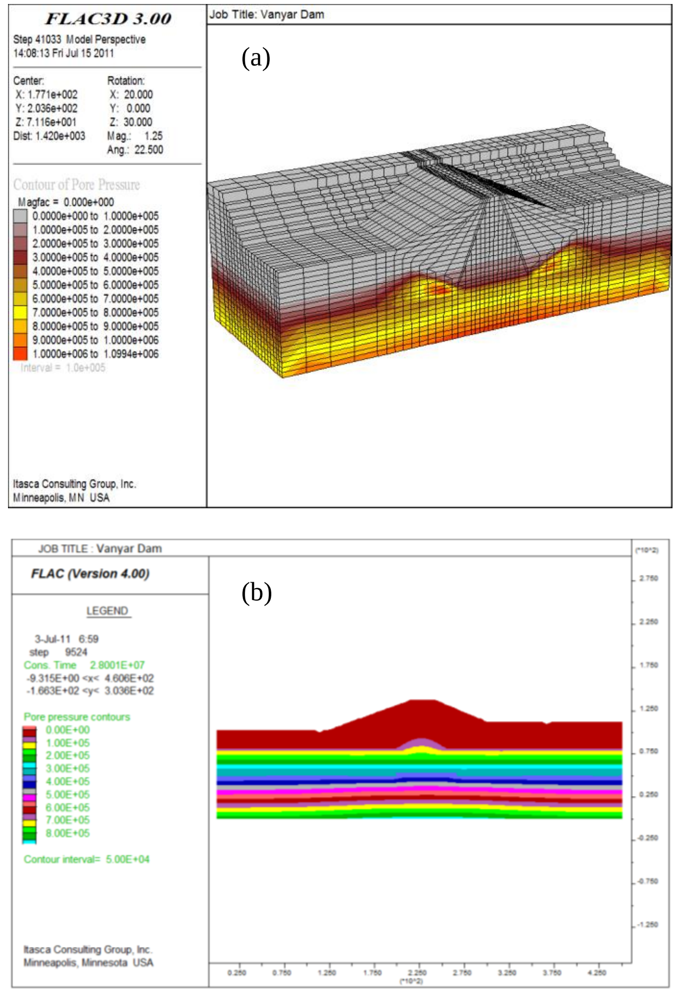


Fig.9. Contours of pore water pressures for "C" cross-section a. three-dimensional numerical model and b. two-dimensional numerical model

According to Fig 9, it seems that both models have almost the same approach and values for pore water pressure. In addition, the level of water in the core is located at the level of ground water table in the alluvial foundation. The installed piezometers in the core show that the pore pressure has been dissipating above the level of water in the core.

The results show that there is a good agreement between the pore water pressures obtained from three dimensional analysis and those recorded by the instruments utilized. The average difference between the pore pressure in the three-dimensional numerical results and instruments is about 4% within cross-section "C". Furthermore, this value is reported about 18% for the two-dimensional numerical results. Fig 10 depicts the variation of pore pressures for the core axis in the "C" cross-section which is obtained from three and two dimensional analyses as well as the instruments.

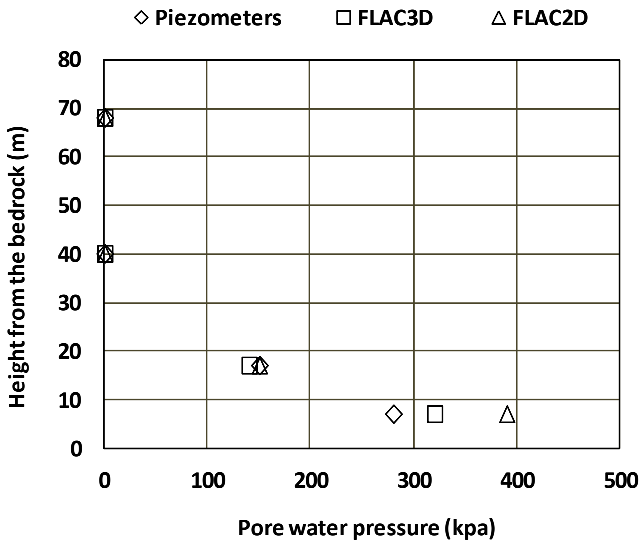


Fig. 10 variation of pore pressure for the core axis in the "C" cross-section obtained from three and two dimensional analysis and instruments

CONCLUSION

In this study, the results of three and two-dimensional numerical analyses have been compared to the data recorded by the instruments in the body of the Vanyar dam. The conclusions are as follows:

1. The settlements obtained from the numerical analysis are fewer than those recorded by the instruments because of the lack of compaction around the instruments.
2. In the upper half of the dam (h/2 to h), the results of the three and two-dimensional analyses are near each other. In the lower half of the dam (0 to h/2), the two-dimensional numerical analysis predicts the settlements more than those obtained from the three-dimensional analysis. This is due to the lack of plane strain conditions caused by the specific geometry of narrow valleys.
3. The total vertical stresses, recorded by the pressure cells, are less than those obtained from the numerical analysis. In addition, the two-dimensional numerical analysis predicts the total vertical stresses more than those predicted by the three-dimensional numerical analysis.
4. The pore water pressures obtained from the numerical analyses are in good agreement with those recorded by piezimeters. Certain differences between these values are due to the estimation of the ground water level in up-stream and down-stream areas as well as the assumption of homogeneity for the core materials in terms of permeability.

According to the results gained by the numerical analysis and the instruments in three parts of the settlement, total vertical stress, and pore water pressure, it can be concluded that the results of the numerical analyses are in good agreement with the data recorded by the instruments. It shows that the assumptions made in the numerical models about the material properties are consistent with reality.

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